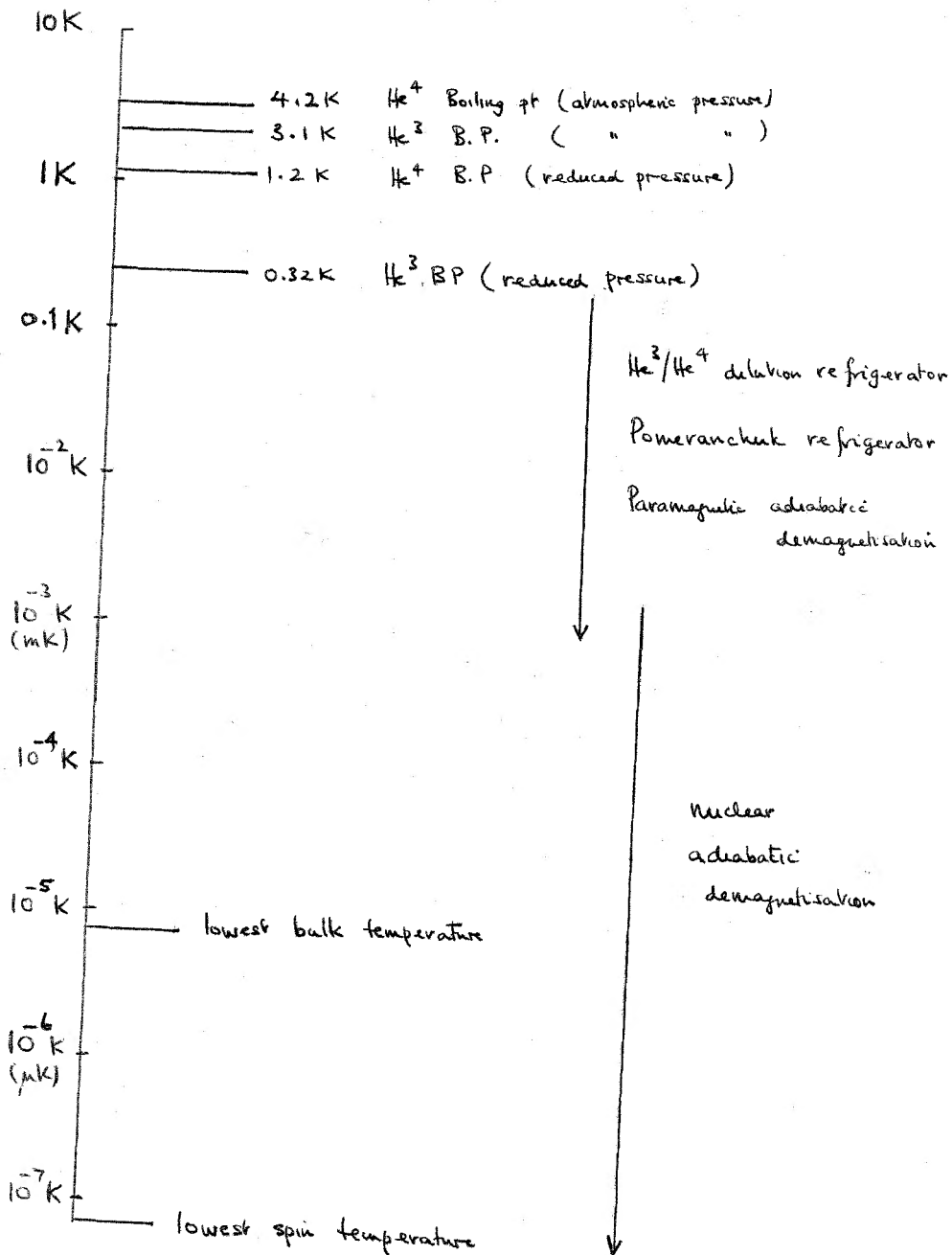


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## Low temperature scale and methods of cooling.

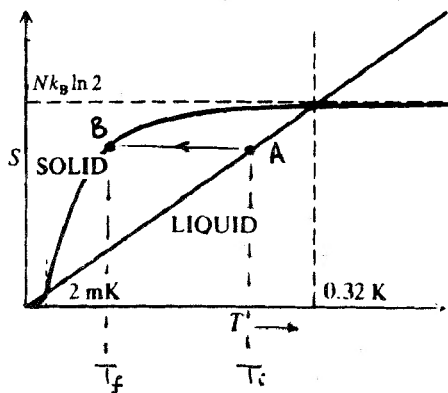


(192)

Cooling methods spanning  $1\text{ K} \rightarrow 1\text{ mK}$ .

1. Pomeranchuk cooling — Principle.

Working substance  $\text{He}^3$



$\text{He}^3$  phase diagram in range  $2\text{ mK} \rightarrow 0.32\text{ K}$  shows entropy of liquid  $\text{He}^3$  less than solid.

Occurs because disorder due mainly to nuclear spins — in solid (localised atoms) spin states populated according to Boltzmann statistics — because atoms are distinguishable (by site position).

In liquid (Fermi gas) Pauli principle imposes spin  $\uparrow \downarrow$  in each state

192a

System of distinguishable atoms  $s = 1/2$

—  $\epsilon$

—  $0$

At temp  $T$

Entropy

$$S = Nk \ln [1 + \exp(-\epsilon/kT)] + \frac{Nk (\epsilon/kT) \exp(-\epsilon/kT)}{[1 + \exp(-\epsilon/kT)]}$$

As  $kT \gg \epsilon$

$$\exp(-\epsilon/kT) \rightarrow 1$$

$$S \rightarrow Nk \ln 2.$$

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Method.

Initial state - quantity of liquid  $\text{He}^3$  at  $\sim 0.2 \text{ K}$

Compress adiabatically.

Adiabatically  $\equiv \left\{ \begin{array}{l} \text{at constant } S \\ \text{no energy flows in or out} \\ \text{of system.} \end{array} \right.$

System of  $\text{He}^3$  goes  $A \rightarrow B$  on diagram.

Temperature falls from  $T_i \rightarrow T_f$ .

Takes place in compression cell - thermally insulated.

Any sample to be cooled - attached to cell.

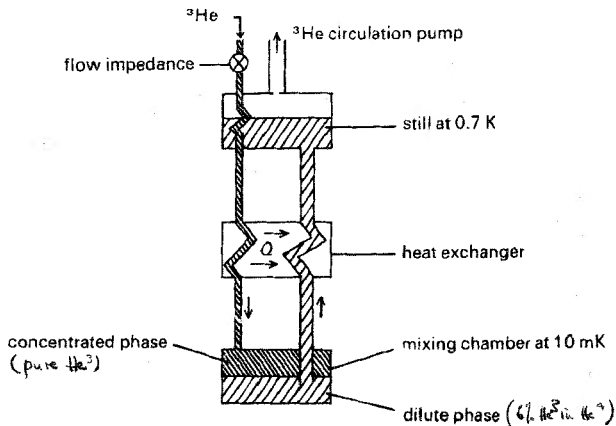
$\text{He}^3 / \text{He}^4$  dilution refrigerator.

Main method for cooling to  $\sim 1 \text{ mK}$ .

Recall from study of  $\text{He}^3 / \text{He}^4$  liquid mixtures that at  $T < 0.86 \text{ K}$  mixture of  $\text{He}^3$  and  $\text{He}^4$  forms phase separated system.

At  $T \sim 0.2 \text{ K}$  - layer of pure  $\text{He}^3$  floats on top of layer of  $\sim 6\% \text{ He}^3$  in  $\text{He}^4$ .

Schematic diagram of refrigerator.



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## Action of refrigerator.

Cooling caused in mixing chamber when atoms of pure (concentrated)  $\text{He}^3$  cross phase boundary into 6%  $\text{He}^3$  (dilute) phase.

Like evaporation from liquid to gas - heat removed from pure  $\text{He}^3$  phase - causes temperature in mixing chamber to fall to mK.

To keep continuous cycle going

Dilute phase connected to still.

In still surface of liquid pumped - extracts  $\text{He}^3$  atoms preferentially as gas

Gas circulated to pure  $\text{He}^3$  input

Cooled through still (0.7 K)

Cooled through heat exchanger (mK)

and back into pure  $\text{He}^3$  phase in mixing chamber

Any sample attached to mixing chamber.

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3. Paramagnetic adiabatic demagnetisation.

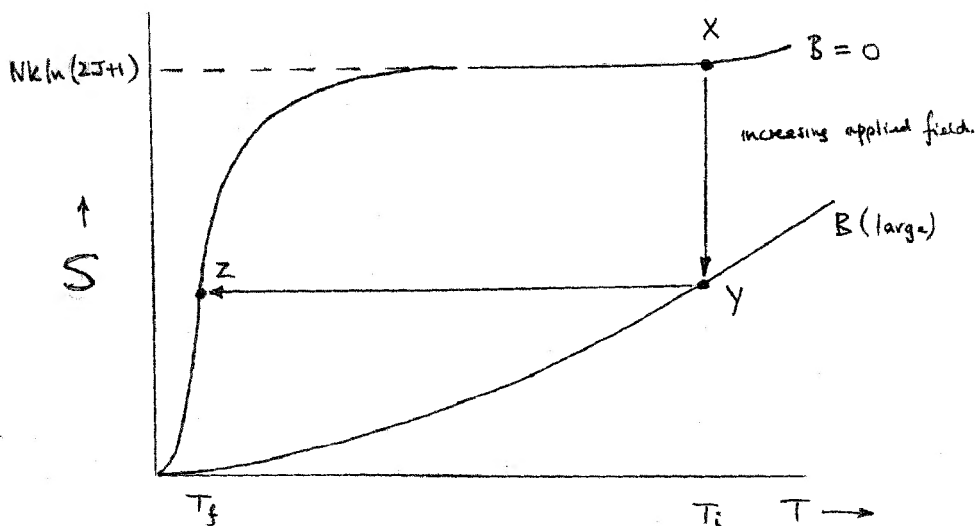
Method as described below - reaches mK.

Method spanning mK  $\rightarrow$   $\mu$ K.

Nuclear adiabatic demagnetisation

System - sample of metallic copper (Cu)

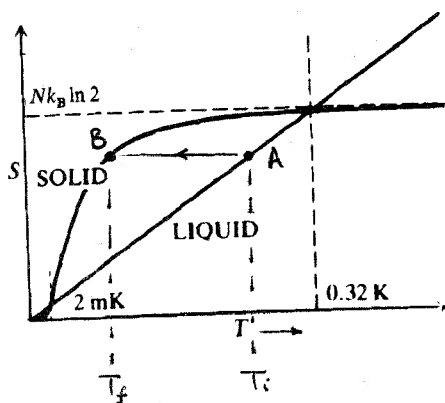
At mK starting temperature main cause of entropy (disorder) is random (quantised) orientations of nuclear spin  $I$  and associated magnetic moments.



Cooling methods spanning  $1\text{ K} \rightarrow 1\text{ mK}$ .

1. Pomeranchuk cooling — Principle.

Working substance  $\text{He}^3$



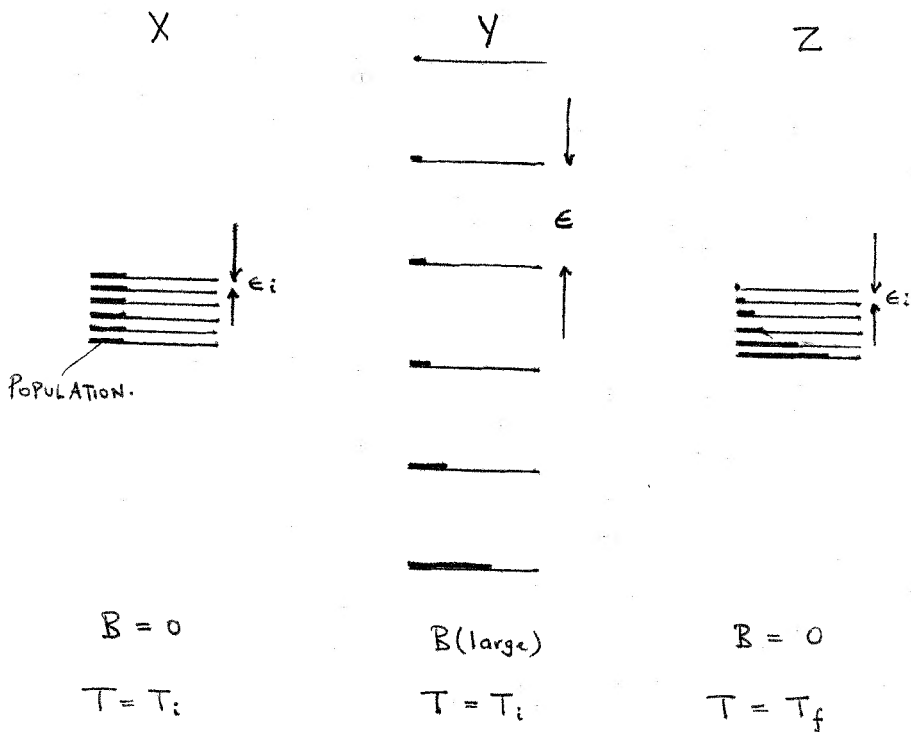
$\text{He}^3$  phase diagram in range  $2\text{ mK} \rightarrow 0.32\text{ K}$  shows entropy of liquid  $\text{He}^3$  less than solid.

Occurs because disorder due mainly to nuclear spins — in solid (localised atoms) spin states populated according to Boltzmann statistics — because atoms are distinguishable (by site position).

In liquid (Fermi gas) Pauli principle imposes spin  $\uparrow\downarrow$  in each state



## Nuclear Energy Levels.



## Method

(i) Start at  $T_i \sim 1 \text{ mK}$

Energy levels of  $\text{Cu}$  nuclei have very small splitting  $\epsilon_i$ :

States approximately equally populated since  $\epsilon_i \ll kT$

Hence  $\exp(-\epsilon_i/kT) \sim 1$

(ii) Apply strong magnetic field  $B$

Causes large splitting of energy levels.  $\epsilon = g\mu_N B$

Now  $\epsilon \gg kT$  thus  $\exp(-\epsilon/kT) \ll 1$

Now population adjusts

Energy given out - since heavy population of low energy states.

Sample in contact with mK refrigerator - which takes this heat away.

Transition  $X \rightarrow Y$  on diagram

(ii) Thermal contact between sample and mK refrigerator broken.

Field B switched off adiabatically  $\left\{ \begin{array}{l} \text{no change in } S \\ \text{no energy flow in} \\ \text{or out of sample} \end{array} \right.$

Energy levels return to stage (i)

but with populations of stage (ii)

Means  $\exp(-\epsilon_i/kT_f) \ll 1$

Hence  $T_f \ll T_i$

Transition  $Y \rightarrow Z$  on diagram

$T_f \sim \mu K.$

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What limits the final temperature  $T_f$ ?

In sample magnetic moments of Cu nuclei set up small internal magnetic field  $B_i$

— this causes the splitting  $\epsilon_i$

When large external field  $B$  applied effective field

$$B_e = \{B^2 + B_i^2\}^{1/2}$$

In cooling transition  $Y \rightarrow Z$

$S$  is constant

but  $S$  is a function of  $(B/T)$  only

thus in  $Y \rightarrow Z$   $(B/T)$  is constant

Hence at  $Y$   $\frac{B_e}{T_i} = \frac{B_i}{T_f} \leftarrow \text{at } Z$

and  $T_f = T_i \frac{B_i}{B_e}$

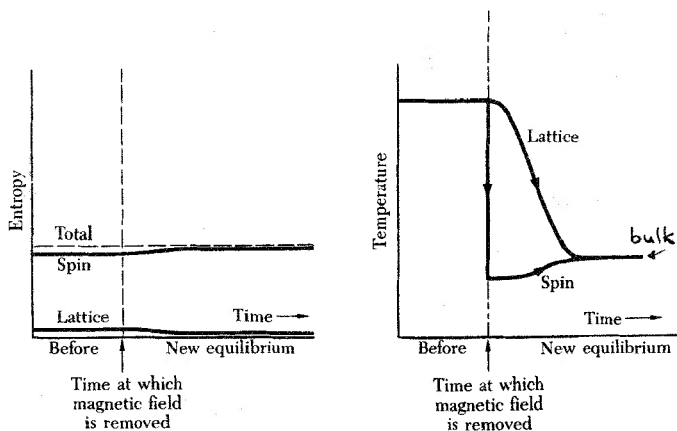
final temp.

Spin temperature / bulk temperature.

Method above cools spin system

To cool bulk of sample spin system and lattice must come to equilibrium. - energy passes from lattice to spins.

Schematic diagram



When spin and lattice in equilibrium - have achieved bulk cooling.

(201)

Can we go lower in temperature?

If system still has some disorder  
and you can affect this by applying some  
external condition (pressure, magnetic field...)  
then by reducing the entropy you can get  
to lower temperature

If there is no entropy left in the system that  
you can influence - then cannot lower temperature.